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Oxygen Charge State Abundance in the Inner Magnetosphere

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13. ABSTRACT (*Maximum 200 words*)

The CRRES Magnetospheric Ion Composition Sensor (MICS) was used to obtain the relative oxygen charge state abundances in the earth's inner magnetosphere ($3 < L < 7.5$). These abundances were obtained for average and quiet ($Kp \leq 2+$, $|DST| < 11$) conditions. They are presented as normalized spectra and compared to the predictions of Spjeldvik and Fritz (1978). These comparisons show that the observed spectra agree best with the Spjeldvik and Fritz predictions that assume an O^+ source, at the high L boundary in their model, for oxygen with $Q \leq +3$ but agree better with their predictions for a solar wind source, O^{+6}, for oxygen with $Q > +3$ on average. As expected, O^+ is the dominant oxygen ion at all times in the inner magnetosphere for energies >60 keV/Q. During average conditions the $Q \geq +4$ ions have fluxes comparable to O^{+3} in the $L = 4.5 - 7.5$ region and are about 50% of the O^{+3} fluxes in the $L = 3 - 5$ regions. Thus, the average O^{+3} fluxes appear to represent a transition state between ionospheric and solar wind source oxygen.

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Introduction

Over the last two decades there have been numerous observations of magnetospheric ion composition, first at the lower energies (< 30 keV/q) by the S3-3, SCATHA, DE-1 and other satellites and later at extended energies by the AMPTE CCE (see Gloeckler et al., 1987 and references therein). These results focused on the major ion species H^+, He^+, He^{++} and O^+ . More recently there have been reports on the higher charge states of oxygen and M > 4 ions (Christon et al., 1994) in the outer magnetosphere. These have complemented the extensive results obtained in the interplanetary medium (Gloeckler and Geiss, 1989), in the magnetosheath (Gloeckler et al., 1986) and preliminary results in the magnetosphere (Kremser et al., 1985 and 1987).

The Christon et al. (1994) results provide a reference data set and boundary population for the transport of all ions into the inner magnetosphere. While several models and calculations have focused on describing the transport of the major ion species inward to form the ring current (Cornwall, 1972; Spjeldvik and Fritz, 1978; Sheldon and Hamilton, 1993; Chen et al, 1993, Sheldon, 1994) only Spjeldvik and Fritz,1978 (hereafter denoted as S & F) have attempted to describe the distribution of oxygen ions. At the time S & F were developing their model only ion mass-composition was available for energetic oxygen (E_O > 30 keV). Yet, in an attempt to match the observed oxygen ion spectra, S & F generated a model which predicted the oxygen charge state distributions for a wide range of energies in the inner magnetosphere and ring current for the two major oxygen sources, solar wind (O^{+6}) and ionosphere (O^+), as separate calculations. In this report we will provide the first observations of oxygen charge state spectra in the inner magnetosphere and will compare the observations with the predictions of S & F.

Observations

For this study we used the ion charge state determination capabilities of the Magnetospheric Ion Composition Sensor (MICS) on the CRRES satellite (Wilken et al., 1992) to obtain the oxygen charge state spectra. The MICS sensor measures ions using time-of-flight (TOF), energy-per-charge (E/q) and total energy (E) measurements for each ion detected (Wilken et al., 1992). The energy per charge measured ranges from 1 to 425 keV/q in 32 logarithmic steps. The parameters E, TOF and E/q are used to determine the energy, mass and charge state of the ions. To obtain the relative oxygen intensity at each charge state we used the highest resolution three-parameter or DE data where the TOF, E/q and E are transmitted for a subset of ions measured (~4 events/sec). Because of the limited sampling rates one cannot use the DE data to obtain absolute fluxes. What the DE data do provide, in all instrument modes, is the relative fluxes of ions with different charge states but the same mass. All the MICS DE data from the period 12 January through 17 September 1991 were extracted and tagged with appropriate ephemeral parameters. These data were then ordered by the values of their three parameters and accumulated into arrays of size 256 x 1024 x 32 for each half of a CRRES orbit into 21 bins in L (Roeder et al., 1994). The resultant data base was then sampled in L and according to an activity criterion. First all data from orbits 416-1001 were accumulated into L bins covering the L ranges 3 - 5 and 4.5 - 7.5 for all times to obtain all oxygen ion intensities for average conditions. (Orbits prior to 416 were not used because of the operational mode of the instrument.) Separately, the quiet-time oxygen ion data only were accumulated into the same L bins. The quiet time was defined according to a criterion used by Sheldon and Hamilton (1992) and Roeder et al. (1994). To be considered quiet, the $|D_{ST}|$ and K_P for a data sample had to be ≤ 11 and $\leq 2+$ respectively and also ≤ 16 and ≤ 3 respectively for the previous 24 hours.

These DE data were then examined and the oxygen ions were extracted based on their known E versus TOF dependence (from calibration data). The oxygen ions were binned into ion energy per charge (E/q) and ion total energy (E) intervals (32 X 256 array). A multiple Gaussian fit, as shown in Figure 1, was applied to the resulting intensity versus E for each E/q interval separately. These fits allowed us to extract the relative intensities at the peak of each observed oxygen charge state as a function E/q as indicated by the labels in the example shown in Figure 1.

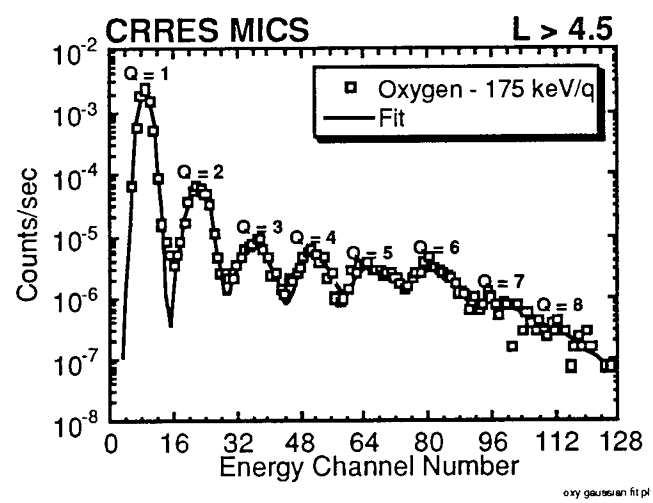

Figure 1 Average 175 keV/q oxygen intensity versus energy channel number for L > 4.5 (square points). The solid curve is a fit to the data using a superposition of Gaussians. The labels on the peaks indicate the oxygen charge states.

These intensities were used to form a spectrum for each charge state. The resultant spectra were normalized to the intensity of the 100 keV/Q O^+ ions. The intensities of the higher charge states ($+2 \leq Q \leq +7$) represent the relative abundances of these ions compared to O^+. Figure 2 shows the resultant normalized oxygen intensities versus energy for all magnetic conditions (top panels) and for quiet conditions (bottom panels) for 4.5 < L < 7 (right panels) and 3 < L < 5 (left panels). These we call the oxygen charge state spectra. These data were averaged over all local times except the interval from 4 to 10 MLT on the morning and pre-noon side and cover the period from 12 January through 17 September 1991.

As was expected and can easily be seen in Figure 2, O^+ is the dominant oxygen ion at all energies in both regions of L for the average and magnetically quiet conditions. The average Kp and D_{ST} for this time period were 3 and -26.7, respectively. The total duration of the quiet intervals was too short to obtain statistically significant counting rates for the higher charge states of oxygen. In the quiet time $3 < L < 5$ region no measure of $O^{\geq+4}$ intensities were obtained, except for a single O^{+4} intensity value at 1500 keV (triangle point in the lower left panel of Figure 2). At higher L the quiet time O^{+4} was well measured, but the O^{+5} was poorly measured and only a single point for O^{+6} was obtained (diamond point near 300 keV in the lower right panel of Figure 2).

We then extracted the relative oxygen ion fluxes at 100 - 200 keV and compared their levels with the predictions of S & F as shown in Figure 3. The MICS O^+ fluxes have been normalized to the S & F fluxes. The S & F curves were generated assuming that O^+ was the source species for oxygen (from S & F's Figure 8). At the lower L the agreement with the first low charge states of oxygen (O^{++} and O^{+++}) is quite good both for the average and quiet conditions. The higher L and higher charge state values are not well represented by the F & S calculation. Still, this is quite good agreement considering the limited source assumption and the fact that S & F did not have charge state information as a reference for their calculations.

Comparison of the MICS oxygen spectra with the predictions of S & F (from their Figure 8) is shown in Figure 4. Again, the MICS O^+ data is normalized to the S & F predictions for O^+ at 100 keV. One sees , like in Figure 3, that the low oxygen charge state spectra agree best with these S & F curves for both the average and quiet conditions. At low L the MICS data and the S & F model predictions agree best for energies below ~200 keV for both average and quiet conditions. At the higher energies the observed spectra are harder than predicted. Also, the higher charge state spectra. are clustered closer together than predicted. This is expected because we are comparing to the S & F prediction based on an assumed O^+ source for the oxygen. Examination of the S & F predicted spectra for an assumed solar wind source (O^{+6}, their Figure 9) shows that they would have the spectra for all the oxygen charge states clustered closer together.

Similarly, at high L the shapes of the observed O^+ spectra for average and quiet conditions are close to the S & F O^+ spectrum ,but the observed spectral shapes for higher charge states are somewhat steeper and closer together. The S & F predictions for the solar wind source would have all the different charge state spectra clustered closer together but with slopes similar to their O^+ source curves. Still, the agreement is reasonably good given the lack of charge state information at the time of their work.

Discussion

A careful examination of Figure 2 shows that, in general, the spectra for O^{++} is consistent with being derived from O^+ via charge exchange. This is expected because the charge exchange cross sections $\sigma_{12} \sim \sigma_{21}$, in the notation of S & F, for the range of energies covered there (see Figures 3 and 4 from S & F) . For O^{+3} the picture is more complicated, as shown in S & F. The cross section for electron capture (charge loss) σ_{32} is a decreasing function of energy,whereas that for electron loss, σ_{23}, (charge gain) is an increasing function of energy with $\sigma_{32} \sim \sigma_{23}$ near 10^3 keV.

At the lower L range, O^{+3} is most likely the transition charge state with comparable contributions from charge loss and charge gain processes from adjacent charge states. For $L \geq 4.5$, under average conditions (top right panel of Figure 2), the O^{+4} intensities are comparable to O^{+3} and those for O^{+5} and O^{+6} are higher. Thus, one may argue that most of the O^{+3} at the higher L must derive from oxygen with charge states $\geq +4$ via charge exchange because $\sigma_{34} < \sigma_{43}$ below ~ 1500 keV. However, it is clear from the relative intensities of the O^{+3} in the other panels that O^{+3} is also derived predominantly from O^{+2} via upward charge exchange. Thus O^{+3} below 1000 keV in energy is a transition charge state separating the oxygen ions that are dominated by the ionosphere as a source from those dominated by the solar wind as a source. What is unclear is which source is dominant for the higher energy oxygen ions.

S & F did well given the limited input data that they had to work with. We know better now, based on the results of Christon et al. (1994), what the real source spectrum for oxygen is and what combination of ionospheric and solar wind ions is required. It is time to utilize these data to redo the S & F calculations. It is clear that such a calculation should be able to match the CRRES MICS data taken in the inner magnetosphere very well

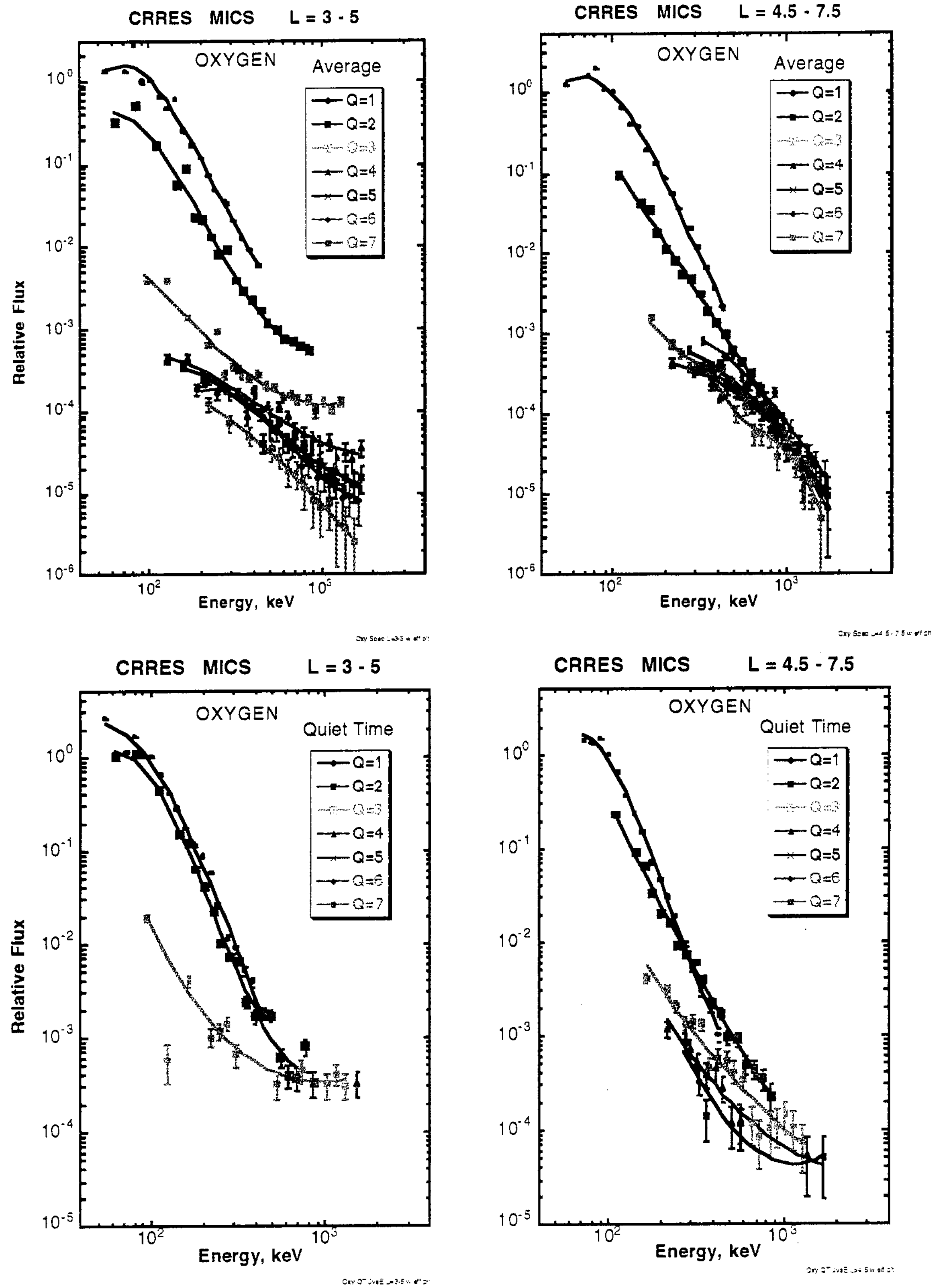

Figure 2 Oxygen charge state spectra for average (top panels) and quiet (bottom panels) conditions and for L = 3 - 5 (left panels) and L = 4.5 - 7.5 (right panels). The energy spectra of the different charge states are color coded as noted in the legends. The spectra are normalized to the O^+ data at 100 keV in each panel.

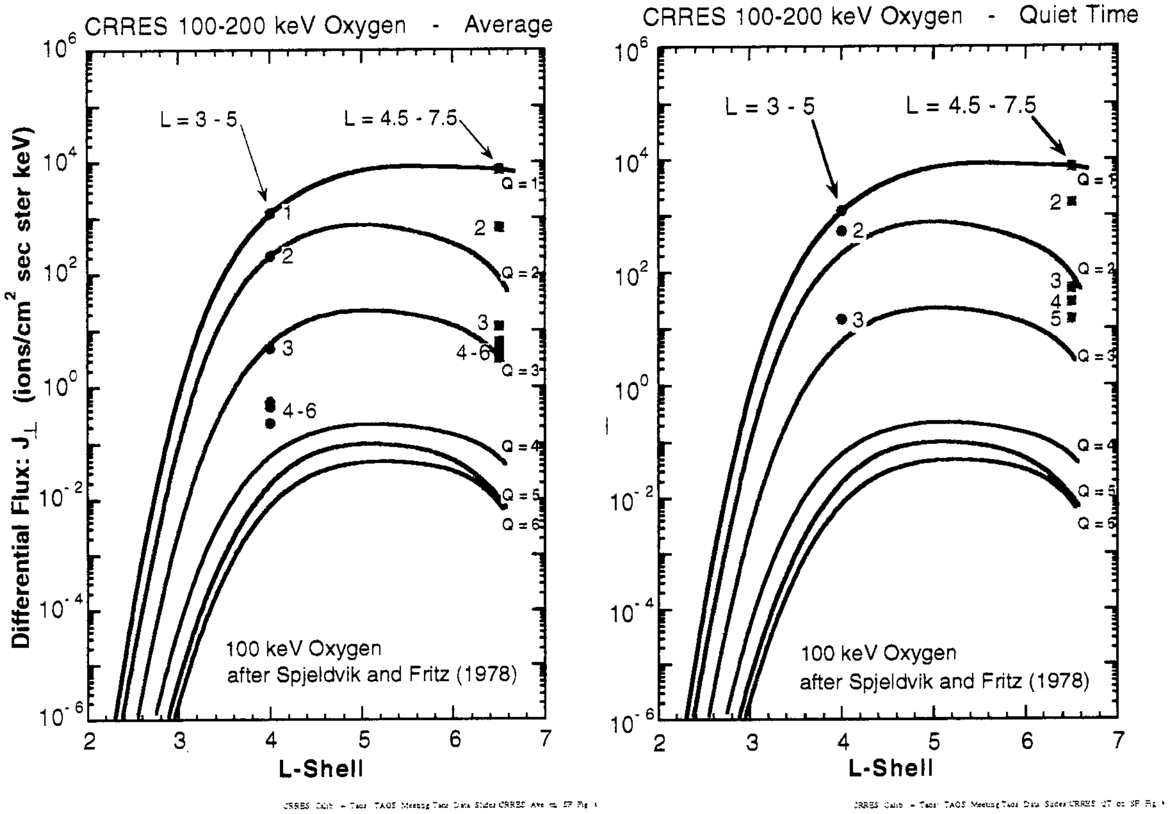

Figure 3 Comparison of CRRES MICS 100 - 200 keV ion intensities for different oxygen charge states with the predictions of Spjeldvik and Fritz (1987) for 100 keV oxygen. CRRES data from two different L ranges and for average (left panel) and quiet (right panel) magnetic conditions. The Spjeldvik and Fritz curves were based on the assumption that O^+ was the only ion in the source region at high L shells ($L > 7$). The CRRES results for O^+ are normalized to the Spjeldvik and Fritz results for O^+.

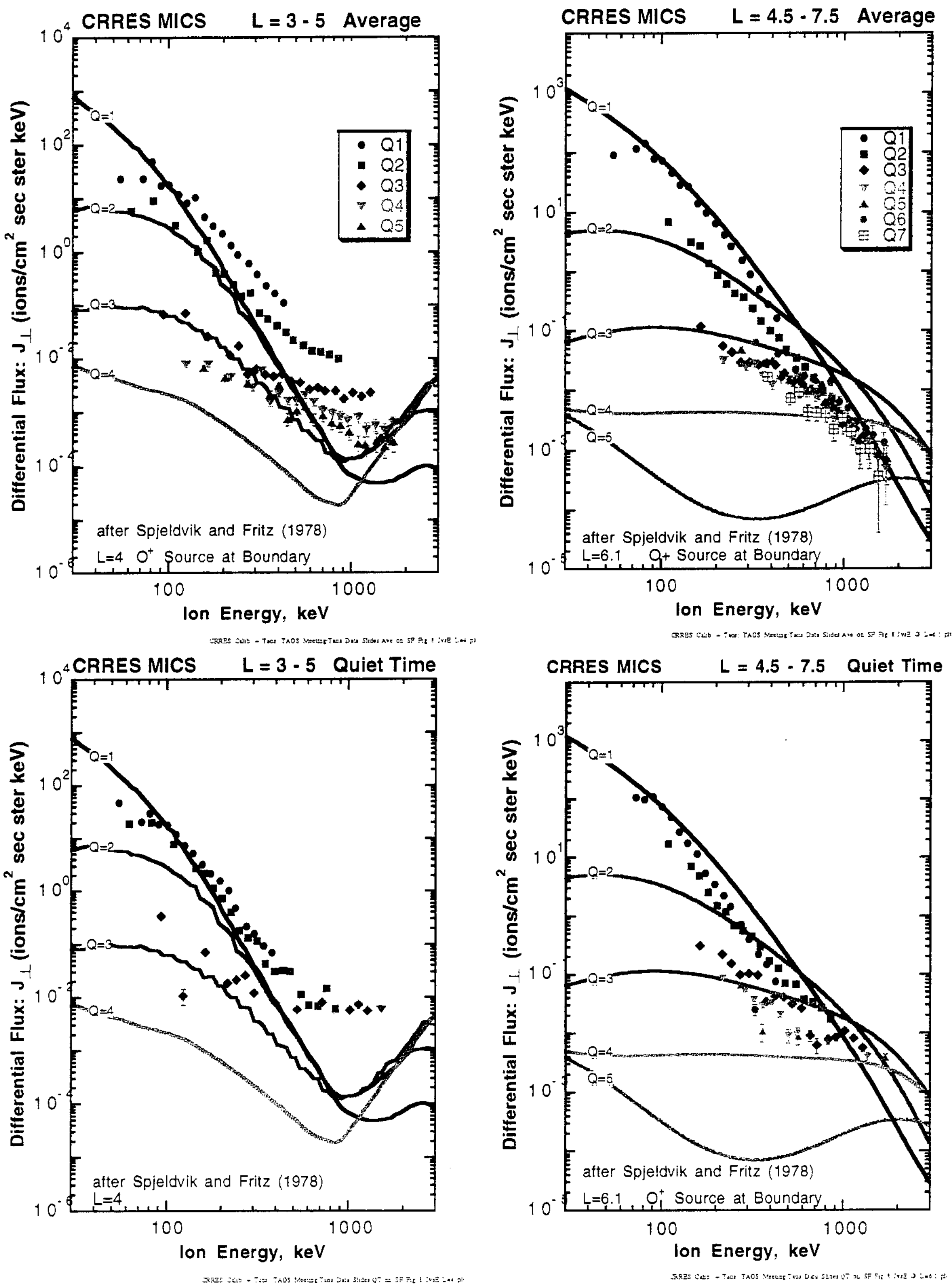

Figure 4 Comparison of CRRES MICS oxygen charge state spectra with the predictions of Spjeldvik and Fritz (1978) for an assumed high L boundary source composed of only O^+. The data are for average magnetic conditions (top panels), quiet times (bottom panels). The MICS data from L = 3 - 5 is compared to S & F results for L~4 (left panels) and MICS data from L = 4.5 - 7.5 is compared to the S & F results for L = 6.1 (right panels).

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